Cause specific mortality risks associated with tropical cyclones in multiple countries and territories: two stage, time series study

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ABSTRACT

OBJECTIVE
To characterise and quantify the mortality risks for a range of causes after tropical cyclones in nine countries and territories.

DESIGN
Two stage, time series study.

SETTING
Nine countries or territories (Australia, Brazil, Canada, South Korea, Mexico, New Zealand, the Philippines, Taiwan, and Thailand), covering tropical, subtropical, and extra-tropical regions.

PARTICIPANTS
General populations living in regions with tropical cyclones in the nine countries or territories, 2000-19.

MAIN OUTCOMES MEASURES
Excess mortality risk of cardiovascular diseases, respiratory diseases, infectious diseases, injuries, neuropsychiatric disorders, renal diseases, digestive diseases, diabetes, and neoplasms as the leading cause of death. Wind speed and rainfall profiles were quantified with a physics based tropical cyclone field model.

RESULTS
14.8 million deaths and 217 tropical cyclone events in communities from the nine countries or territories were included in the analysis. Mortality risks from various causes consistently increased after tropical cyclones, with peaks occurring within the first two weeks after the cyclone, followed by a rapid decline. During the first two weeks after a tropical cyclone, the highest increases were seen in mortality from renal diseases and injuries, with a cumulative relative risk of 1.92 (95% confidence interval (CI) 1.63 to 2.26) and 1.21 (1.12 to 1.30), respectively, for each additional tropical cyclone day. Relatively more modest risks were found for mortality from diabetes (cumulative relative risk 1.15, 95% CI 1.08 to 1.21), neuropsychiatric disorders (1.12, 1.05 to 1.19), infectious diseases (1.11, 1.05 to 1.17), digestive diseases (1.06, 1.02 to 1.09), respiratory diseases (1.04, 1.00 to 1.08), cardiovascular diseases (1.02, 1.01 to 1.04), and neoplasms (1.02, 1.00 to 1.04). Mortality risks were substantially higher in communities with greater levels of deprivation and in those with historically fewer tropical cyclones, especially for renal, infectious, and digestive diseases, as well as for diabetes. Rainfall related to tropical cyclones had a more consistent increasing exposure-response relation with mortality risks, particularly for deaths related to respiratory, cardiovascular, and infectious diseases.

CONCLUSIONS
After tropical cyclones, mortality risk increased variably for different causes, populations, and regions. Integrating epidemiological evidence into the development of management systems for climate extremes is urgently needed, particularly in regions with higher levels of deprivation and in those with historically fewer tropical cyclones. These measures are necessary to improve the adaptive capacity in responding to the growing risks and shifting activity of tropical cyclones in a warming climate.

WHAT IS ALREADY KNOWN ON THIS TOPIC
Tropical cyclones are the costliest climate disasters and an important public health concern given the expanding coastal populations and expected increase in intensity with a warming climate

Population based studies on the effects of multiple tropical cyclones on health are lacking, are focused mainly on the US, and are especially limited in regions with historically fewer tropical cyclones and hence less resilience

Existing evidence on extreme weather events mainly focuses on all cause or limited cause mortality, with consistent and quantitative assessments lacking for a broad range of causes and countries

WHAT THIS STUDY ADDS
Beyond injuries, tropical cyclones were associated with increased mortality risks for a range of causes, particularly renal diseases

Mortality risks could be substantially higher in socioeconomically deprived populations and in communities with historically fewer tropical cyclones

Rainfall, rather than wind speed, seemed to be a stronger mortality risk indicator, especially for respiratory, cardiovascular, and infectious diseases

Introduction
Globally, tropical cyclones rank among the most devastating and costly climate extreme events. Annually, tropical cyclones affect an average of 20.4 million people and have caused mean direct economic losses of US$51.5 billion (£38.3 billion; €43.8 billion) over the past decade.[1] Critically, the proportion of intense tropical cyclones is projected to increase with global warming.[2 3] Stronger, more active, and longer lasting cyclones than previously recorded were seen in recent cyclone seasons.[4-6] Ageing and rapidly expanding coastal populations could further increase exposure to, and adverse affects of, tropical cyclones.[7] Exposure to such extreme events is and will continue

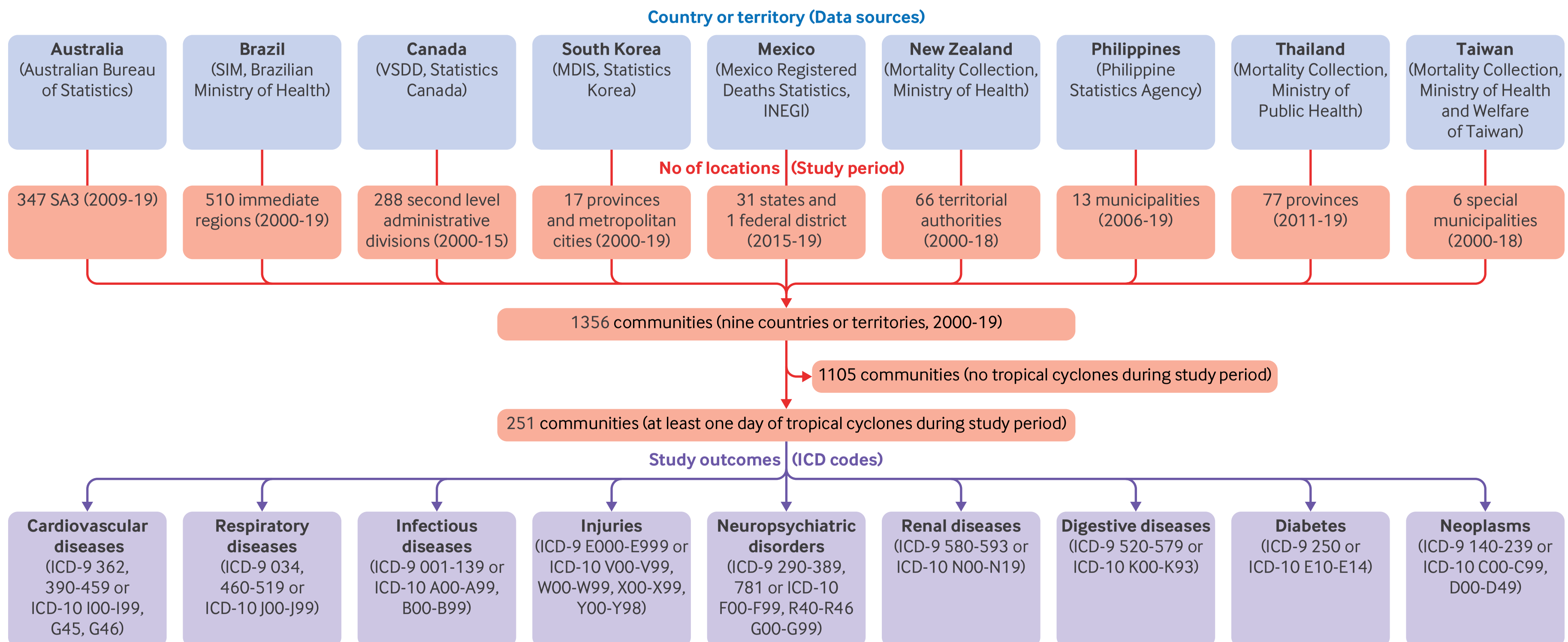

Fig 1 | Flowchart of data collection and organisation procedures. ICD=international classification of diseases; INEGI=Instituto Nacional de Estadística y Geografía (National Institute of Statistics and Geography); MDIS=microdata integrated system; SIM=Sistema de Informação sobre Mortalidade (Mortality Information System); VSDD=vital statistics deaths database

to be a major public health concern and a key driver of hazards related to climate change. Epidemiological evidence on the effects of tropical cyclones on populations is limited globally, however, which has important implications for understanding the health effects of cyclones and for developing informed response strategies to mitigate these health burdens.[8]

Tropical cyclones can affect population health both directly and indirectly. Direct effects, such as injury and drowning caused by the physical forces of tropical cyclones, are well recorded and established.[1] In contrast, indirect effects, arising from disruptions caused by tropical cyclones, such as interruptions to water and food supplies, damage to infrastructure, environmental contamination, psychosocial stress, and lack of access to healthcare services, are largely unclear and historically have been overlooked in disaster management systems.[9-11] Emerging evidence, including several large scale studies of multiple tropical cyclones over decades, indicates an association between tropical cyclones and an increased risk of various causes of death, including cardiovascular diseases and neuropsychiatric conditions.[8 12-14] Most of these studies, however, focused on the impact in the US, followed by China.[8] Populations in other countries are under-represented, especially those in regions with limited historical experience and potentially lower resilience to tropical cyclones. Populations in these regions may be more vulnerable because of inadequate adaptation to the migration of tropical cyclones under a changing climate.[15]

Furthermore, previous studies have mainly relied on wind speed related to tropical cyclones as the only exposure metric. Precipitation induced by tropical cyclones, however, may also be an important and independent contributor to disease dynamics and public health outcomes.[16] Also, the exposure-response relations between the characteristics of tropical cyclones (ie, wind force and precipitation) and cause specific mortality have not been described. These relations are the essential evidence base for an effective disaster management system. Overall, a comprehensive and consistent assessment of cause specific mortality risks in the aftermath of tropical cyclones in multiple countries and regions is needed. In this study, we integrated representative mortality data over two decades from nine countries and territories. Our aim was to quantify the risk of mortality from a variety of causes after a tropical cyclone and to characterise the exposure-response relations of wind force and rainfall with these risks. We also sought to identify populations vulnerable to these cause specific mortality risks to inform disaster management and preparedness efforts.

Methods

Mortality data

We collected individual mortality records from 1356 communities in Australia, Brazil, Canada, South Korea, Mexico, New Zealand, the Philippines, Thailand, and Taiwan over various periods between 2000 and 2019 (table S1). These countries and territories represent a wide range of socioeconomic and tropical cyclone characteristics, including tropical regions frequently affected by cyclones (eg, Taiwan and the Philippines) and extra-tropical areas with fewer cyclones (eg, Canada and New Zealand). Moreover, these countries have diverse healthcare infrastructures and socioeconomic conditions, with both higher resource settings (eg, Australia, Canada, and South Korea) and lower resource settings (eg, Vietnam, Brazil, Mexico, and Thailand). This diversity allowed us to capture regional variations and socioeconomic inequalities in the effects of tropical cyclones, and so advance our understanding of the effects on global health. Mortality data were obtained from national and local authorities within each country or territory, including information on the residence community, and date, sex, age, and cause of death of each individual. Figure 1 and supplementary text S1 have details on data sources, collection and organisation procedures, as well as the representativeness of the data for each country or territory. The cause of death, defined as the main disease or injury that initiated the events directly leading to death, was categorised based on ICD-9 and ICD-10 (international classification of diseases 9th and 10th revisions) codes. We classified causes of death into nine categories: cardiovascular diseases, respiratory diseases, infectious diseases, injuries, neuropsychiatric disorders, renal diseases, digestive diseases, diabetes, and neoplasms (text S1).

Deprivation, population, and temperature data

To estimate the deprivation level of each community, a global gridded relative deprivation index at a spatial resolution of 0.01° (about 1 km^2) was obtained from the Socioeconomic Data and Applications Centre (SEDAC). SEDAC calculated the overall relative deprivation index between 2010 and 2020 for each grid by integrating various factors, including child dependency ratio, infant mortality rates, and the human development index.[17] Values ranged from 1 to 100, with higher values indicating a higher level of deprivation. We calculated the community level deprivation index by averaging the relative deprivation index values of grid cells within the geographical boundary of each community. To estimate the population centre of each community to assess exposure, we also obtained annual population count data at 0.01° spatial resolution across the globe for the years 2000-19 from LandScan.[18] Specifically, the population data were first calibrated for each country or territory in each year to be consistent with data from the United Nations, as detailed in our previous work.[19] Then, the population weighted centroid was calculated for each community in each year, based on the calibrated grid specific population counts within each community boundary. Finally, we obtained near surface ambient temperature from the ERA5 (European Centre for Medium Range Weather Forecasts Reanalysis 5) land reanalysis dataset to estimate the population weighted daily average temperatures for each community.[20] We calculated the population weighted temperature for each community by averaging temperatures from all intersecting grid cells, weighted by both the population within each cell and the proportion of the cell area overlapping the community boundaries.

Tropical cyclone assessment

We used an improved wind field model[21] that has been widely applied in previous studies[22-24] to estimate the temporal dynamics of the wind fields associated with historical tropical cyclones. The detailed methodology has been described in our previous work.[14 25 26] Briefly, we inputted the global cyclone characteristics from the International Best Track Archive for Climate Stewardship (IBTrACS)[27] into a parametric wind field model and generated global gridded daily maximum sustained wind speeds associated with each cyclone event in IBTrACS. Wind speeds were first computed at a high spatiotemporal resolution (1/12° and hourly) and then aggregated to obtain a spatial resolution of 0.5° (about 55 km^2) and daily according to local time zones. We defined a tropical cyclone exposure day for each community as a day when the maximum wind speeds reached or exceeded 17.5 m/s in the grid cell of the community's population centroid.[12 28] Furthermore, cumulative rainfall on tropical cyclone exposure days was derived from the ISIMIP3a dataset with a physics based tropical cyclone rainfall model.[29 30]

Statistical analysis

We applied a standard two stage, time series analytical framework to estimate mortality associated with tropical cyclones.[31-34] Because of the relatively limited number of tropical cyclone days and mortality counts for some diseases, we analysed the data on a weekly time scale.[12 35] In the first stage, for each community, a quasi-Poisson regression and distributed lag non-linear model was used to quantify relative risk, with 95% confidence intervals (CIs), of cause specific mortality for each additional tropical cyclone day in a week. The quasi-Poisson and distributed lag non-linear model account for possible overdispersed mortality counts and delayed effects of tropical cyclones on mortality.

Specifically, we modelled tropical cyclone exposure days with a distributed lag term of up to four weeks after the cyclone with a natural cubic spline function of two internal knots (with an intercept) equally placed on the log scale of lag weeks.[36] We selected a maximum lag of four weeks because, in our preliminary analysis, mortality risks for some causes (eg, injury) associated with a tropical cyclone decreased rapidly over time and did not persist beyond four weeks after the cyclone. Long term temporal trends in mortality counts were controlled through a natural cubic spline function of calendar year with four degrees of freedom (df) in the model. To account for seasonal trend and annual differences between years, an interaction term between calendar year and a natural cubic spline function of week of year (df=6) was included.[37 38] Potential confounding by ambient temperature was controlled by including a weekly average temperature in the model.[12] The number of knots and degrees of freedom were chosen to minimise the Akaike information criterion of the model, with alternative options explored in sensitivity analyses.

In the second stage, the effect estimates of each community generated from the first stage were pooled in a multivariate random effect meta-analysis. To identify potentially vulnerable subpopulations to cause specific mortality risks associated with tropical cyclones, we derived overall and subgroup specific effect estimates based on sex (women *v* men), age group (<60 *v* ≥60 years), community level relative deprivation index (lowest 50% *v* highest 50%), frequency of tropical cyclones, and country or territory. The significance of the effect modifications was tested with a Wald-type test on the effect estimates across groups.[39]

Finally, to characterise the exposure-response associations between maximum wind speed and cumulative rainfall related to tropical cyclones and mortality, we estimated the mortality risks for each additional cyclone day, based on different wind speed and rainfall thresholds. The trend for these risks was modelled with a dose-response meta-analysis with natural cubic splines, with two internal knots at the 25th and 75th centiles of the exposure distribution.[40] Figure S2 shows a causal diagram illustrating the hypothetical relations between tropical cyclone wind speed, rainfall, and mortality.

We assessed the sensitivity of our results by: controlling the natural variations in mortality counts, with different degrees of freedom for calendar year (3, 5, or 6) and week of year (4, 5, 7, or 8); using different temperature adjustments (by removing temperature from the model or controlling for temperature with a natural cubic spline function of 3, 4, or 5 degrees of freedom); and using double negative control models to reassess the relations between tropical cyclones and mortality. Double negative control models are designed to identify and correct for biases that may arise from unmeasured confounders, enhancing causal inference in observational studies.[41 42] Supplementary text S2 has more details on the double negative control model and its application in this study.

Data collection, organisation, and analysis for this study were conducted according to a prespecified analysis plan (https://osf.io/q5mr4/files/osfstorage). Any modifications to the analysis plan are also detailed here. All analyses were performed in R software (version 4.1.3)[43] with the R packages dlnm[44] and mixmeta[45] for the first and second stage analysis, respectively. A two sided Pvalue of <0.05 was considered significant.

Patient and public involvement

This study was based on deidentified, aggregated death registration data, which inherently precludes the direct involvement of patients or their relatives in the research design, conduct, reporting, or dissemination because of privacy and security regulations across countries. Furthermore, no funding was allocated for

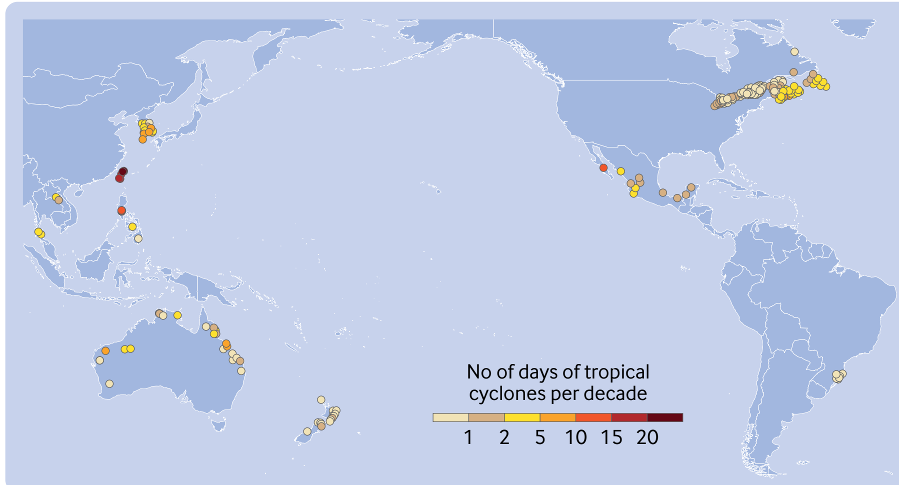

Fig 2 | Geographical distribution of communities in the nine study countries or territories that had at least one tropical cyclone day during the study period (n=251), along with counts of tropical cyclone days per decade

patient or public involvement, and given the nature of the data, such engagement was not feasible.

Results

Descriptive statistics

Mortality data from 1356 communities were generally representative of the general population in each study country or territory (supplementary text S1). Of these communities, 251 that experienced at least one tropical cyclone day during the data collection period were included in the analysis, with a total of 217 unique tropical cyclone events (some tropical cyclones affected multiple communities simultaneously, table S1). Figure 2 illustrates the spatial location of these communities and the frequency of tropical cyclones. Communities in Taiwan, the Philippines, southern areas of South Korea, and the west coast of Mexico experienced tropical cyclones most frequently (≥10 tropical cyclone days per decade), whereas tropical cyclones were less frequent in Australia, Brazil, Canada, New Zealand, and Thailand (<5 days per decade). We included 14.8 million deaths in the analysis from communities in the nine study countries or territories; neoplasms (about 4.6 million) and cardiovascular diseases (4.3 million) were the leading causes of death overall, and in sex, age, and country or territory subgroups (table S2).

Overall cause specific mortality risks from tropical cyclones

The mortality risk from various causes consistently increased and peaked in the first two weeks after a tropical cyclone (fig 3). The increased risks fell rapidly and generally dissipated beyond two weeks, particularly for deaths related to injuries. Hence we focused on the short term effects of tropical cyclones and examined the cumulative mortality risks within the first two weeks in subsequent analyses.

Overall, mortality from renal diseases and injuries showed the highest increases in the two weeks after tropical cyclones, with a cumulative relative risk of 1.92 (95% CI 1.63 to 2.26) and 1.21 (1.12 to 1.30), respectively, for each additional tropical cyclone day in a week (fig 4 and table S3). In contrast, we found relatively more modest risks for mortality from diabetes (cumulative relative risk 1.15, 95% CI 1.08 to 1.21), neuropsychiatric disorders (1.12, 1.05 to 1.19), infectious diseases (1.11, 1.05 to 1.17), digestive diseases (1.06, 1.02 to 1.09), respiratory diseases (1.04, 1.00 to 1.08), cardiovascular diseases (1.02, 1.01 to 1.04), and neoplasms (1.02, 1.00 to 1.04).

Cause specific mortality risks by age group and sex

Men had significantly higher mortality risks from neuropsychiatric disorders, renal diseases, and diabetes (P for difference <0.05) than women after tropical cyclones (fig 4 and table S3), but women had a higher risk of mortality from respiratory diseases and injuries. We did not find significant effect modifications by sex for mortality from other causes of death, with a consistently increased mortality risk for both women and men.

We found significant differences between age groups in mortality risk for respiratory diseases, neuropsychiatric disorders, and renal diseases (P for difference <0.05; fig 4 and table S3). Specifically, individuals aged <60 years had significantly higher risks for respiratory diseases and neuropsychiatric disorders, whereas those aged ≥60 years had higher risks for renal diseases. The risks of cardiovascular, infectious, and digestive diseases, injuries, diabetes, and neoplasms were not significantly different between age groups, with similar increases in both groups.

Cause specific mortality risks by deprivation, frequency of tropical cyclones, and country or territory

Mortality risks from tropical cyclones were consistently greater in the higher relative deprivation index group than in the lower deprivation group for various causes of death (fig 4 and table S3). We saw the greatest

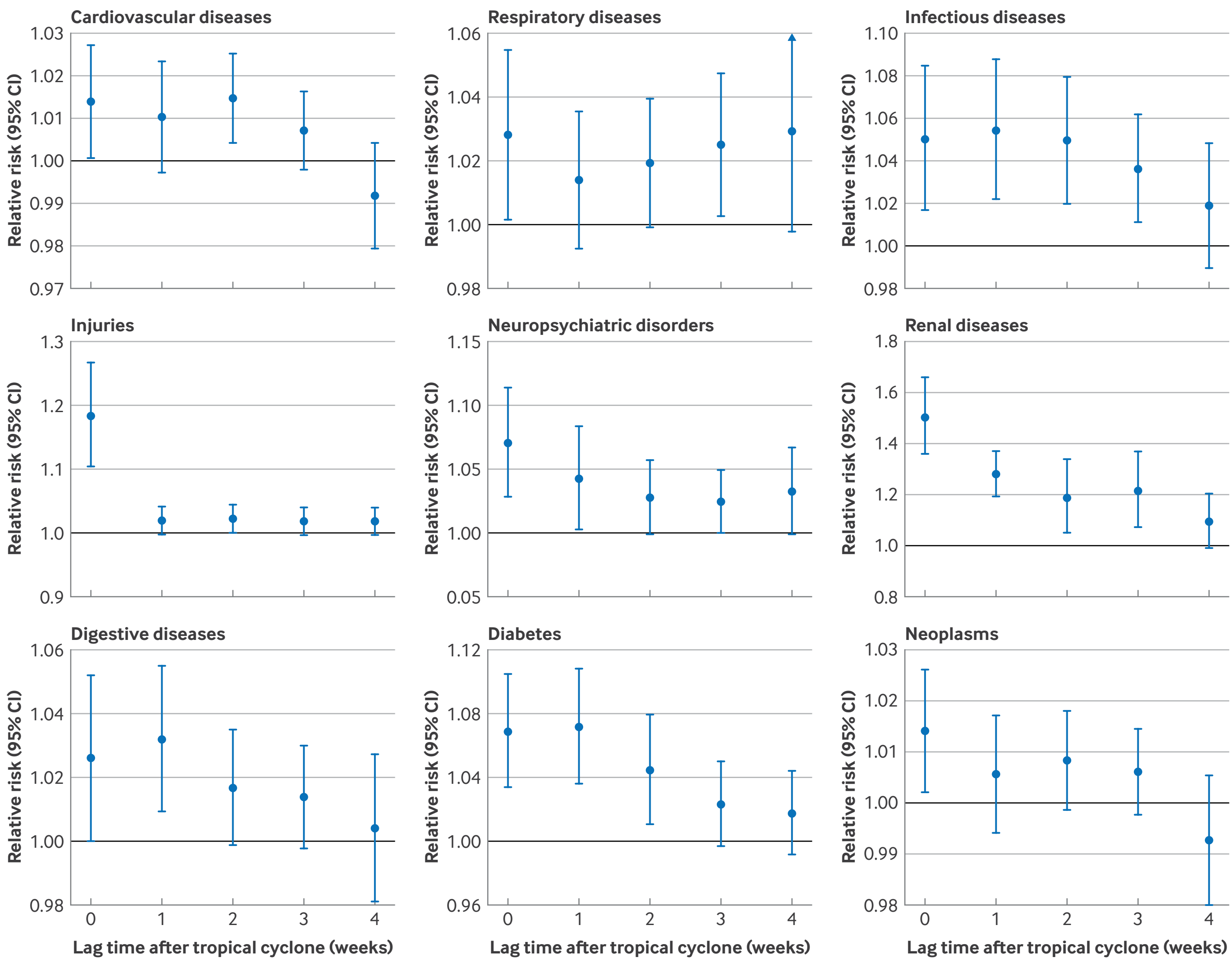

Fig 3 | Overall relative risks of cause specific mortality for each additional day over 0-4 weeks after a tropical cyclones. Dots and whiskers indicate point estimates and 95% confidence intervals (CI), respectively

differences between groups for renal, infectious, and digestive diseases, and diabetes, with communities in the higher relative deprivation index group showing significantly higher mortality risks (P for difference <0.05) than those in the lower deprivation group. When we examined mortality risks by frequency level (measured as tropical cyclone exposure days per decade, divided into three equal groups), communities with historically less frequent tropical cyclones (groups 1 and 2) generally had substantially higher cause specific mortality risks than those with the highest frequency for tropical cyclones (group 3), particularly for renal, infectious, and digestive diseases, and diabetes (fig S3 and table S4).

Generally, we found increased cause specific mortality risks associated with tropical cyclones for all countries and territories (table S3). Mortality risks for various causes increased consistently in Australia. Significantly high mortality risks were detected for infectious, renal, and digestive diseases, and diabetes in Canada; respiratory diseases and neuropsychiatric disorders in New Zealand; and infectious diseases in South Korea (P <0.05). The magnitude of the risks at the country or territory level, however, generally had a higher level of uncertainty to reach significance.

Exposure-response relations

Figure S4 shows the distributions of maximum sustained wind speed (m/s) and cumulative rainfall (mm) on tropical cyclone days. For mortality risks from injuries, neuropsychiatric disorders, and diabetes, we found a super linear increasing trend as the maximum sustained wind speed increased for a cyclone exposure day (fig 5). Mortality risks increased rapidly when maximum sustained wind speed exceeded about 35 m/s. We did not see these increasing trends for cardiovascular, respiratory, infectious, renal, or digestive diseases, or for neoplasms. For these causes of death, the level of uncertainty increased substantially with higher maximum sustained wind speeds.

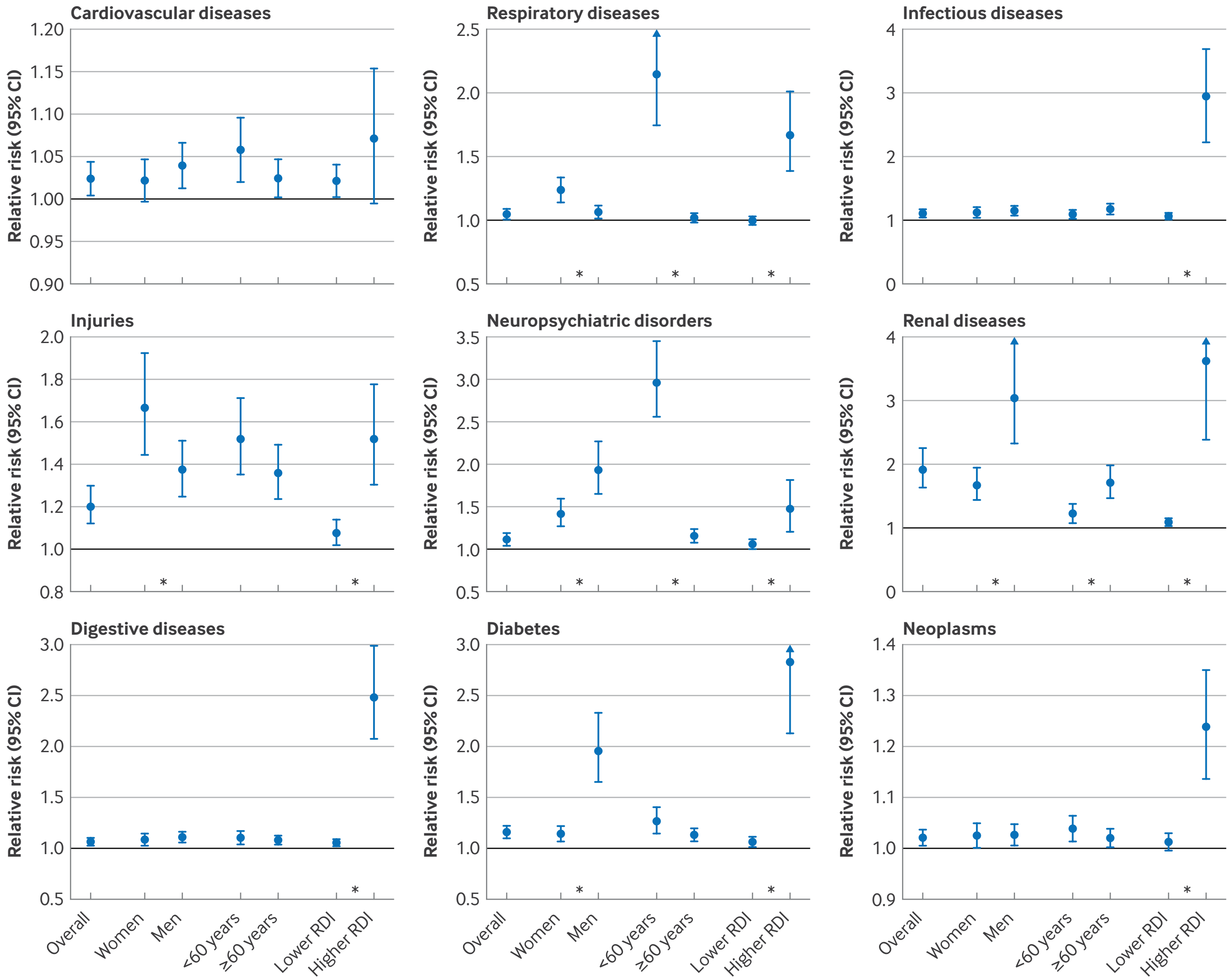

Fig 4 | Overall and subgroup specific cumulative relative risk of cause specific mortality for each additional day during the first two weeks after a tropical cyclone. Subgroup analysis was performed by sex, age, and relative deprivation index (RDI) level (lowest 50% v highest 50%). Dots and whiskers indicate point estimates and 95% confidence intervals (CI), respectively. *P<0.05 for differences between groups

We saw similar trends in cause specific mortality risks for cumulative rainfall, except for cardiovascular, respiratory, and infectious diseases (fig 6). Mortality risks from injuries, neuropsychiatric disorders, and diabetes increased consistently with maximum sustained wind speed or cumulative rainfall. Increasing trends in risks of cardiovascular, respiratory, and infectious diseases, however, were found only for rainfall and not for wind speed.

Sensitivity analysis

The results were robust across different model specifications, giving similar cause specific mortality risk estimates for models with different degrees of freedom to control for time trends (figs S5 and S6) and temperature (fig S7), as well as for models with or without temperature adjustment (fig S8). The risk estimates from the double negative control models generally did not differ substantially from those of the main models, except for renal diseases, where the magnitude of the risk decreased in the double negative control models (fig S9).

Discussion

Principal findings

Based on two decades of data from nine countries and territories, we quantified and characterised the health effects of tropical cyclones. We found that tropical cyclones were associated with increased mortality risks from various causes. Mortality risks from renal, infectious, and digestive diseases, as well as diabetes, were substantially higher in communities with greater levels of deprivation and lower frequency of tropical cyclones. Wind speed associated with tropical cyclones seemed to be more strongly associated with mortality risks than rainfall, especially for cardiovascular, respiratory, and infectious diseases.

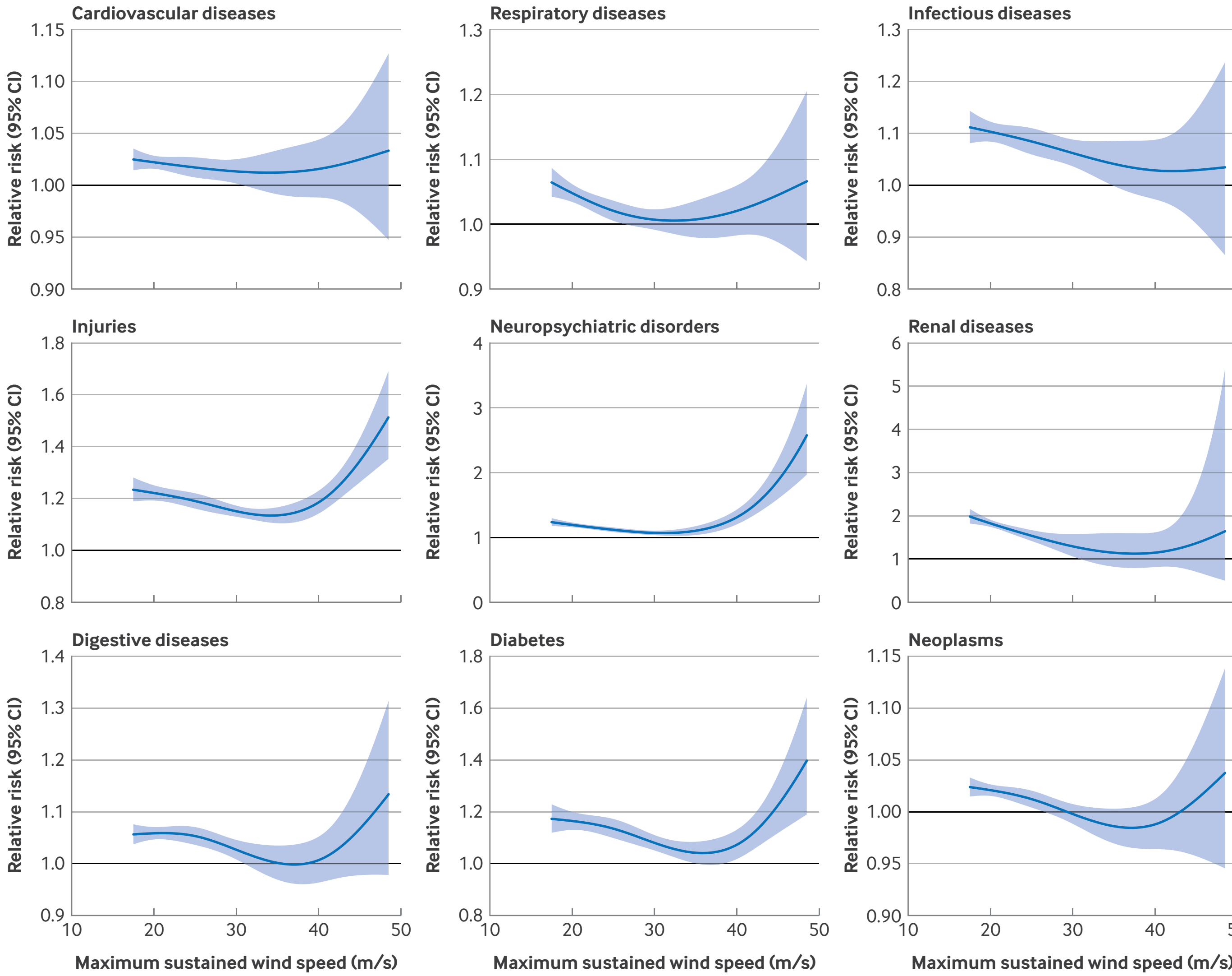

Fig 5 | Overall cumulative relative risk of cause specific mortality for each additional cyclone day, based on different thresholds of maximum sustained wind speed over the first two weeks after a tropical cyclone. Lines and shaded areas indicate point estimates and 95% confidence intervals (CI), respectively

So far, evidence is lacking on the effects of tropical cyclones or related events (eg, intense wind speed or rainfall) on a range of causes of death over decades, and especially across multiple countries. Our previous systematic review noted that studies quantitatively assessing mortality risks associated with tropical cyclones have largely focused on the US, examining all cause mortality related to one tropical cyclone event (eg, Hurricane Katrina and Hurricane Sandy) within a specific year or geographic area.[8] These studies had substantial inconsistency in modelling strategies and results, limiting the comparability and generalisability of their findings. Only a few studies have examined the health risks of tropical cyclones and extreme rainfall events in different countries and regions, and these have assessed all cause mortality, and cardiovascular and respiratory diseases, but with no differential risk assessments by age or sex.[14 26 46-48]

To our knowledge, only two case-crossover studies have examined cause, age, and sex specific mortality risks associated with tropical cyclones.[12 49] The first study, based on mortality data from China, 2013-18, focused on the immediate risks after tropical cyclones and found increased mortality risks for cardiovascular and respiratory diseases on the day of exposure.[49] The second study, based on US mortality data, 1988-2018, took a longer term perspective and found increased death rates for a broader range of causes, including infectious and parasitic diseases, respiratory and cardiovascular diseases, and neuropsychiatric conditions, during the month after the tropical cyclone.[12] Our main findings are consistent with those from the US study, supporting increased mortality from a range of different causes in the weeks after a tropical cyclone, across several countries and territories. Compared with the modest and marginally significant risk estimates in the US study, however, we saw much

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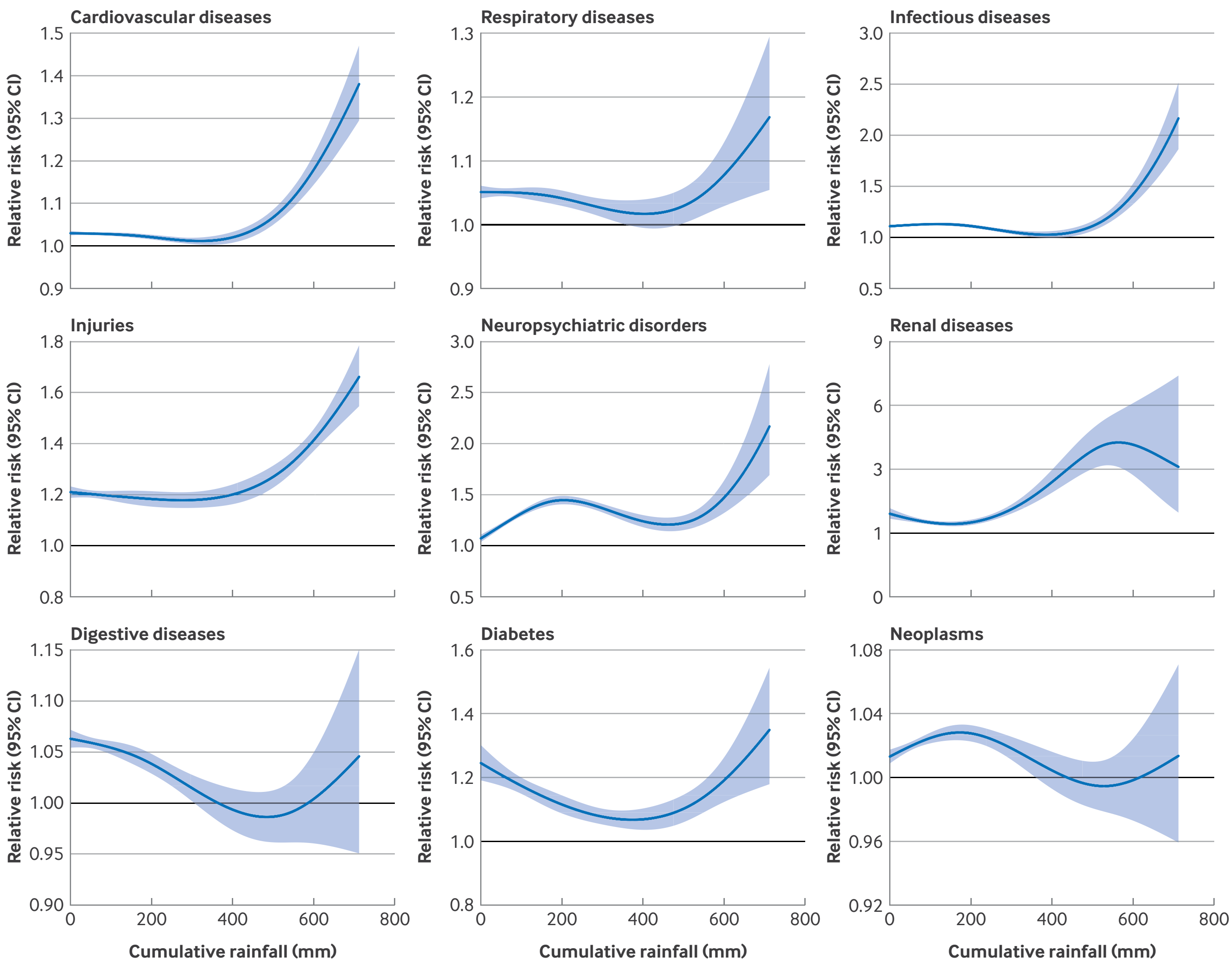

Fig 6 | Overall cumulative relative risk of cause specific mortality for each additional tropical cyclone day, based on different cumulative rainfall over the first two weeks after a tropical cyclone. Lines and shaded areas indicate point estimates and 95% confidence intervals (CI), respectively

higher mortality risks in the aftermath of tropical cyclones, particularly for injuries, cardiovascular diseases, and infectious diseases. This discrepancy may reflect greater resilience to tropical cyclone hazards in the US than in other countries and territories.

Extreme weather events, such as tropical cyclones, are expected to cause and exacerbate diseases, both directly and indirectly.[8] The direct effects are acute and caused by the physical effects of tropical cyclones. As expected, we found an increased mortality risk from injuries, peaking in the first week and decreasing substantially, tending to be minimal after two weeks. Compared with the direct physical effects, indirect effects are more complex and are largely unclear, but include health risks arising from disruptions related to the cyclone, stressors, or induced events (eg, evacuation and displacement, power outage, and loss of resources and livelihoods).[8] As well as injuries, our results indicated an increased mortality risk from tropical cyclones for non-communicable diseases (particularly renal diseases, diabetes, neuropsychiatric disorders, and digestive diseases) and infectious diseases. Data on the epidemiology of tropical cyclones are limited, however, and the underlying mechanisms contributing to the differential risks seen across disease categories are still not clear.[8] This inequality could be attributed to the combined effects of disruption of essential healthcare services, limited access to drug treatments, and increased physical and psychological stress. For example, patients with renal disease are especially susceptible to life threatening complications when haemodialysis schedules are interrupted by the effects of tropical cyclone events, such as power and water outages, leading to fluid overload and electrolyte imbalances.[50]

We found that mortality risks, especially those related to cardiovascular, respiratory, and infectious diseases, seemed to be more strongly associated with rainfall than wind speed from cyclone events. This finding could be related to several factors. Firstly, tropical cyclones characterised by high rainfall are more likely than those with high wind speeds to cause flooding and water contamination, spreading infectious diseases and limiting access to medical care and management of chronic health conditions. Secondly, the health impacts of rainfall are generally more indirect, and potentially more widespread and persistent than those of high winds, which tend to be more transient and direct in nature. Evidence of the effects of rainfall or heavy rainfall events related to tropical cyclones on public health outcomes is limited, however, particularly for exposure-response relations for a broad spectrum of diseases.[46] In this study, we have characterised potential exposure-response curves for various diseases associated with extreme weather events, like tropical cyclones. Our data support the development of informed disaster management systems to respond to the growing health risks in a changing climate.

We found strong evidence indicating variations in mortality associated with tropical cyclones in different subpopulations. The results suggested distinct sex and age related vulnerabilities to mortality risks, although these patterns were generally mixed across causes of death. Currently, evidence is limited on potential effect modifiers for different causes of death in vulnerable populations in the aftermath of extreme weather events, such as tropical cyclones, limiting our understanding of the observed complex mortality risk patterns. Differences in physiology, activity pattern (eg, mobility level),[51-53] awareness (eg, disaster preparedness),[11] and social support[54] are potential contributing factors. For example, individuals aged <60 years had higher respiratory mortality risks for respiratory diseases, likely related to exposure to greater environmental hazards (eg, mould allergens) during recovery activities after a cyclone,[55] whereas those aged ≥60 years had higher risks from renal diseases, likely attributable to exacerbation of pre-existing chronic conditions (eg, hypertension and chronic kidney disease) by stressors such as interruptions in healthcare.[56]

We identified consistently higher mortality risks for various causes among populations residing in communities with a higher relative deprivation index than those with a lower deprivation index. After tropical cyclones, mortality risks from renal, infectious, and digestive diseases, and diabetes were substantially higher in communities with a higher relative deprivation index than those with a lower deprivation index. Individuals and communities with lower socioeconomic status often have greater losses and have more difficulty recovering because of disproportionately inadequate disaster responses, such as insufficient resources and infrastructure for evacuation and medical care, during and after tropical cyclones.[57] Our findings highlight the substantial health inequities that exist and underscore the urgent need for targeted interventions and improved disaster preparedness and response strategies in socioeconomically deprived communities.

Studies on the epidemiology of tropical cyclones in multiple countries are scarce. Previous studies in multiple countries on health risks related to other environmental factors, such as air pollution and temperature, also found strong evidence indicating spatial heterogeneity in associated mortality risks across countries and regions.[31 32] Compared with the mortality risks associated with air pollution and temperature,[31 32] however, our effect estimates, although generally increased, had substantially higher uncertainty (ie, wide 95% CI) at the country and territory level. This uncertainty, mainly because of the limited number of tropical cyclone exposure days, complicated precise detection of area specific mortality risks and increased the variability in the effect estimates. This finding underscores the necessity for studies on multiple tropical cyclones over decades and across regions, with improved and consistent assessment of exposure, to obtain robust conclusions.

Differences in social vulnerability, healthcare access, and disaster preparedness in the diverse socioeconomic and infrastructural contexts of the studied communities could also have contributed to the observed risk variations across countries and territories. In particular, we found that socioeconomic development (measured by the relative deprivation index) was a strong effect modifier for the associations between mortality and tropical cyclones, with risks in areas of lower socioeconomic development tending to be substantially higher. Also, we found that the risk estimates could be substantially higher in communities that historically had fewer tropical cyclones. This finding may indicate a possible adaptive response to tropical cyclones in populations residing in areas with a higher frequency of tropical cyclones and a lack of effective response systems in areas with fewer tropical cyclones. Given the poleward migration of tropical cyclones (ie, more tropical cyclones are expected in higher latitude areas that were previously less exposed, such as New Zealand and Canada, for example), developing and implementing effective disaster preparedness and response strategies in these regions to mitigate future health risks is urgently needed.

Strengths and limitations of this study

We investigated mortality risks for a variety of causes in the aftermath of tropical cyclones in different countries and territories. By using a consistent exposure and risk assessment strategy in a large sample of nine countries and territories with a wide range of exposure levels, and with diverse sociodemographic, infrastructural, and health service conditions, our study had greater statistical power and thus better generalisability and comparability than previous studies conducted in one country.

Our study had some limitations. The possibility of residual confounding cannot be completely excluded. Similar results from the sensitivity analysis with a causal statistical model (ie, double negative control model) indicates, however, that the influence of residual confounding is likely to be modest.[41] Furthermore, our exposure assessment was conducted at the community level, assigning the same exposure to all individuals within a community, despite variations in individual experiences of tropical cyclones. This approach may introduce Berkson-type and classical exposure measurement error that could inflate the variance of our effect estimates[58] and bias them towards the null,[59 60] indicating that our results are likely conservative.

Also, given the limited evidence on exposure-response curves for the effects of tropical cyclones on health, potentially because of the scarce and discontinuous nature of tropical cyclones, we characterised the potential exposure-response curves by meta-analysing risk estimates for different exposure groups. This approach extends previous studies that mainly reported subgroup specific risks grouped by exposure levels.[12 28 33] Unlike traditional exposure-response curve methods that rely on continuous dose-response modelling in one population, our dose-response meta-analysis synthesised risks across heterogeneous populations and exposure thresholds to deal with the limited data, which may reduce the precision and accuracy of the estimated exposure-response curves, especially at high exposure levels.

Moreover, our analysis relied on the number of tropical cyclone exposure days, precluding simultaneous adjustment for wind speed and rainfall, and full separation of their effects. This limitation likely did not substantially affect our main findings, however, because landfall wind and rainfall after a tropical cyclone largely decouple and likely affect health by distinct pathways.[14 61-63] Finally, because we used high quality established mortality data from nine countries and territories, we did not include other countries that are potentially vulnerable to tropical cyclones (eg, Bangladesh, Myanmar, and Vietnam) but have limited evidence on the health effects of tropical cyclones.[26] This limitation hinders the generalisability of our findings on a global scale. Future studies from these regions could complement the data from this study.

Conclusions and policy implications

Our study has provided compelling and quantitative evidence indicating increased mortality risks from various causes after tropical cyclones in multiple countries and territories. We identified disproportionately higher mortality risks in socioeconomically deprived communities, particularly for renal, infectious, and digestive diseases, as well as for diabetes. Targeted disaster management strategies are urgently needed to prioritise reducing the excessively high mortality risks from these diseases after tropical cyclones in socioeconomically deprived communities. Also, our results indicated higher mortality risks in areas with fewer tropical cyclones, suggesting a potential lack of preparedness and adaptive responses in these regions. Rainfall related to tropical cyclones could be more strongly associated with mortality than wind speed, especially for cardiovascular, respiratory, and infectious diseases. Greater emphasis should be placed on rainfall, alongside wind speed, in the early warning and classification of the hazards of tropical cyclones. Overall, integrating more evidence on the epidemiology of tropical cyclones into disaster response strategies to deal with the growing risks and shifting activity of tropical cyclones under a warming climate is urgently needed.

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Ethical approval: The study used de-identified aggregated mortality data and was approved by the Monash University Human Research Ethics Committee (ID 29141).

Data sharing: Historical information on the temporal dynamics of cyclone events is publicly available from the International Best Track Archive for Climate Stewardship (IBTrACS) data (https://www.ncei.noaa.gov/products/international-best-track-archive). Annual global gridded population count data are publicly accessible from the LandScan Global Population Database (https://www.eastview.com/resources/e-collections/landscan/). Ambient temperature data are publicly available from the ERA5 reanalysis dataset (http://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels). Mortality data were obtained from a collaborative research network under a data sharing agreement and the authors are not permitted to directly share the third party raw data.

Transparency: The lead authors (YG and SL) affirm that the manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

Dissemination to participants and related patient and public communities: The research findings will be disseminated to the broader community by press releases, social media, presentations at international forums, and reports to government agencies and academic societies.

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Web appendix: Supplementary Material